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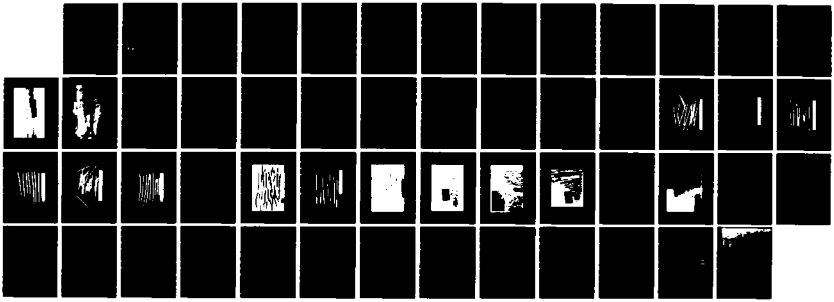

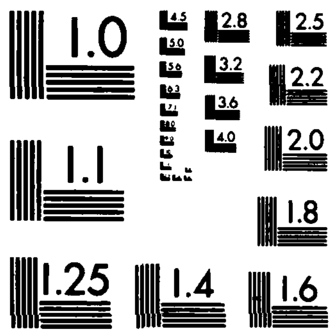

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MEMORANDUM REPORT ARBRL-MR-03296

CONTINUED STUDY OF STICK PROPELLANT COMBUSTION PROCESSES

Frederick W. Robbins
Albert W. Horst

July 1983

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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The interior ballistic performance of propelling charges employing perforated, unslotted stick propellant often cannot be simulated using either lumped-parameter or two-phase-flow models, the experimental maximum pressure being much higher than calculated. A continuation of studies, initiated in FY81, into this anomalous performance has provided experimental evidence that the major contributor to this increase in pressure is splitting of the propellant sticks, a consequence of higher local pressures inside the long

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perforations of the unslotted sticks. Second-order effects include erosive burning or "coning" at the ends of the perforations and augmented burning rates on the progressive interior surfaces caused by the locally increased pressure. Other observations: slotted stick propellant was not found to split inside the gun, though fracturing occurred as the long grains tried to follow gas streamlines upon exiting a short-barreled test fixture; short, unslotted stick propellant, like slotted stick propellant, did not split during the interior ballistic event, yet produced greater muzzle velocities than predicted; and, finally, the NOVA two-phase-flow interior ballistic code provided good simulations of flamespread and pressurization inside the perforation of long, unslotted stick propellant.

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I. INTRODUCTION

Stick propellant is finding increasing application in the world of artillery. In addition to use in several European intermediate and top-zone charges, stick propellant is currently being introduced in the United States as a product improvement to the top-zone (M203) propelling charge for the 155-mm, M198 Towed Howitzer. Further, other intermediate and top-zone applications are under consideration for both current and future US artillery systems.

The selection of the stick propellant geometry for these charges has been, to a large extent, based on several very desirable ballistic advantages associated with its use. Potentially damaging longitudinal pressure waves are all but unseen with stick charges, a consequence of the natural flow channels provided by the bundle of sticks.[1] In addition, regular packing of the sticks permits higher loading densities than achievable with randomly packed granular propellant. This feature allows performance equivalent to that of existing granular propellant charges with a slightly increased mass of a lower-energy, lower-flame-temperature propellant, which, in turn, should increase barrel life and perhaps reduce muzzle flash. We must point out, however, that recent investigation[2,3] of an old concern[4] has confirmed that the same feature of stick propellant that reduces pressure waves also leads to more of the propellant remaining and burning in the gun chamber, increasing total heat input to the origin of rifling, and, at the very least, dampening our optimism for significantly increased tube life with stick propellant. Finally, not yet exploited, has been the alternative choice of using these same larger charge weights of the same or even higher energy propellant in a stick configuration for increased performance from an existing gun.

Unfortunately, in his attempt to realize these potential advantages to the maximum extent possible, the stick propellant charge designer has had to continually face one very frustrating problem largely absent from the granular propellant alternative - the inability to use standard interior

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[1] *F.W. Robbins, J.A. Kudzal, J.A. McWilliams, and P.S. Gough, "Experimental Determination of Stick Charge Flow Resistance," 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol. II, pp. 97-118, November 1980.*

[2] *A.W. Horst, "A Comparison of Barrel-Heating Processes for Granular and Stick Propellant Charges," ARBRL-MR-03193, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1982 (AD A118394).*

[3] *J.A. Lannon, A.J. Bracuti, C.J. Gardner, D. Adams, and G. Sterbutzel, "Wear Testing of M30A1 and M31E1 Propellant Stick Configuration Packaged in Bags and Combustible Cases," Tri-Service Wear and Erosion Symposium, Picatinny Arsenal, Dover, NJ, October 1982.*

[4] *L.W. Nordheim, H. Soodak, and G. Nordheim, "Thermal Effects of Propellant Gases in Erosion Vents and Guns," NDRC Armor and Ordnance Report No. A-262, National Defense Research Committee, Washington, DC, March 1944.*

ballistic models as design tools. The predicted performance of stick propellant, using reasonably uncompromised data bases, always falls somewhat below that achieved in the gun, and, while this sounds like a very enjoyable circumstance to encounter, it also precludes the modeler from providing reliable estimates of the optimum stick geometry for achieving the desired ballistic level. This situation, unhappily, can cost a charge development program many precious months, as the "cut and try" method often requires one or more extra iterations.

Our earlier work,[5] based on separate, lumped-parameter modeling of burning inside the perforations and on the exterior surfaces of unslotted stick propellant, suggested that pressurization inside the perforation over that in the external volume was a strong function of propellant dimensions (Figure 1). The analysis assumed the two computational regions to be coupled by isentropic mass flow relations. Even with a unity discharge coefficient, pressure differentials that exceeded corresponding dynamic measurements of propellant burst strength by more than an order of magnitude were predicted for common stick geometries - a condition which all but assures mechanical failure of the propellant sticks!

Gun firings were then conducted to probe and perhaps quantify this hypothesis. Firings were conducted in a 155-mm howitzer employing unslotted, single-perforated, M30A1 stick propellant, in charges of the same total propellant mass but with the sticks cut to different lengths. While classical interior ballistic theory would predict only minor ballistic differences associated with the small differences in burning surface (i.e., end areas), the results of Table 1 reveal major differences. The longest grains exhibited the highest maximum pressures. These data are at least qualitatively consistent with a hypothesis built on the trends of Figure 1. However, in order to reproduce these results with the model, it was also necessary to speculate that the total additional burning surface associated with splitting was a function of the initial stick length. This added

TABLE 1. FIRING RESULTS FOR THREE LENGTHS OF UNSLOTTED STICK PROPELLANT

Grain Length (mm)	Maximum Pressure (MPa)		Muzzle Velocity (m/s)	
	Average	Range	Average	Range
686	354	-	813	-
343	314	5	799	2
171	263	3	778	5

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[5]*F.W. Robbins and A.W. Horst, "A Si ple Theoretical Analysis and Experimental Investigation of Burnin Proces for Stick Propellant," ARBRL-MR-03295, USA ARRADCOM, Ballistic e sa Laboratory, Aberdeen Proving Ground, MD, July 1983.*

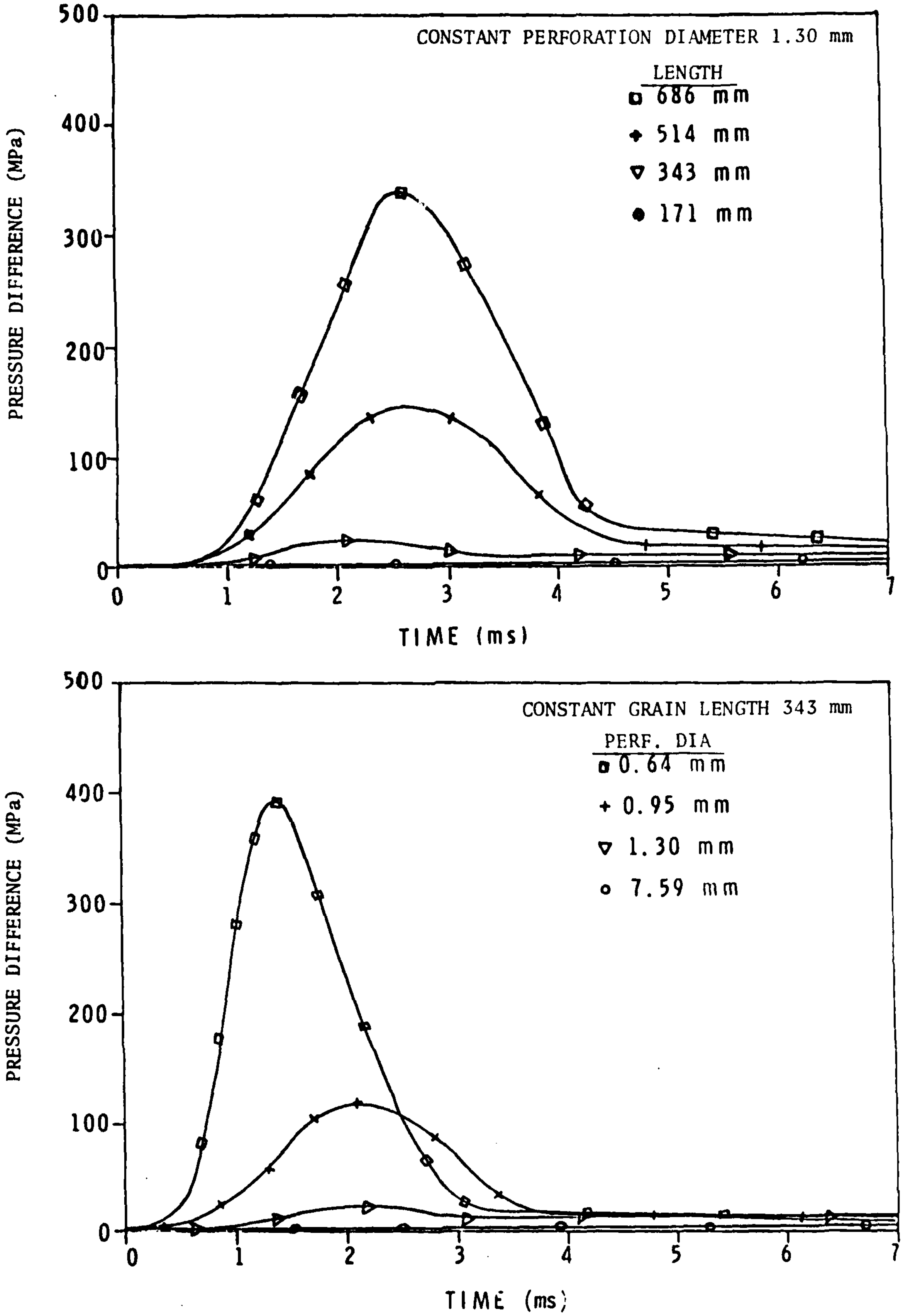

Figure 1. Calculated Pressure Difference Between Perforation and Exterior Region

degree of freedom made it possible to match all observed pressures, though corresponding calculated velocities remained low in all cases.

With this background, we now proceed to describe several experiments conducted to clarify our speculations.

II. EXPERIMENTAL TECHNIQUES

A somewhat more sophisticated device than reported previously[5] was fabricated to measure pressurization within the perforation of a burning propellant stick. The principal improvement was the addition of small chambers at each end of the fixture, shown in Figure 2, for controlling the ignition function. The ignition system consisted of one black powder pellet (0.192 g) initiated by an M100 Match. Initially, igniters were placed in both end chambers in an attempt to provide a uniform pressurization environment; however, ignition at one end was soon adopted as simultaneity of functioning of the two igniters could not be achieved. Four Kistler 607C2 pressure gages were mounted along the length of the propellant stick, with additional gages in the end chambers. The gages were clamped to the propellant stick over small holes drilled through to the perforation in such a way that the propellant itself provided the sealing surface. Micro-Measurements strain gages, Type EA-300250BF-350 and EP-08-125AC-350 were employed in later tests, affixed to the M30A1 propellant sticks with M-Bond 200 adhesive and to the NOSOL 363 propellant samples with M-Bond Type AE.

A second test fixture employed was a 155-mm, short-barreled howitzer, shown in Figure 3. Projectile travel was only about 100 mm; though, due to the finite emptying time of the gun while most of the propellant was still burning, maximum pressures achieved actually corresponded to about 200 mm of travel in a standard howitzer. Collection of extinguished propellant sticks after the firings allowed detailed examination of fractured surfaces and measurement of burned distances. All firings were performed using M101 Projectiles adjusted to a mass of 43.08 kg.

The designations and dimensions of stick propellants used in testing are provided in Table 2. Perforation diameters were measured using Feuer Steel Plug Gage (precision) Pins, a technique found to be fast, in good agreement with optical measurements, and reproducible within 0.02 mm. Outer diameters of the sticks were measured with calipers or a micrometer, and slot widths were determined using an optical comparator.

III. RESULTS AND DISCUSSION

A. Measurements of Pressurization Within the Perforation

Using the "Pressure-Inside-the-Perforation" (PIP) Device of Figure 2, pressure-time curves, such as those shown in Figure 4, were obtained for the various unslotted stick propellants. Surviving portions of the extinguished propellant stick for the same test are depicted in Figure 5. The M30A1 typically split longitudinally into pieces 50- to 100-mm long, though it usually sheared cleanly at the gage clamps, leaving right circular cylinders of propellant the length of these adapters. The NOSOL 363 propellant also split during testing, but usually separated longitudinally into only four or five pieces. Average maximum pressures before fracture of the full-length

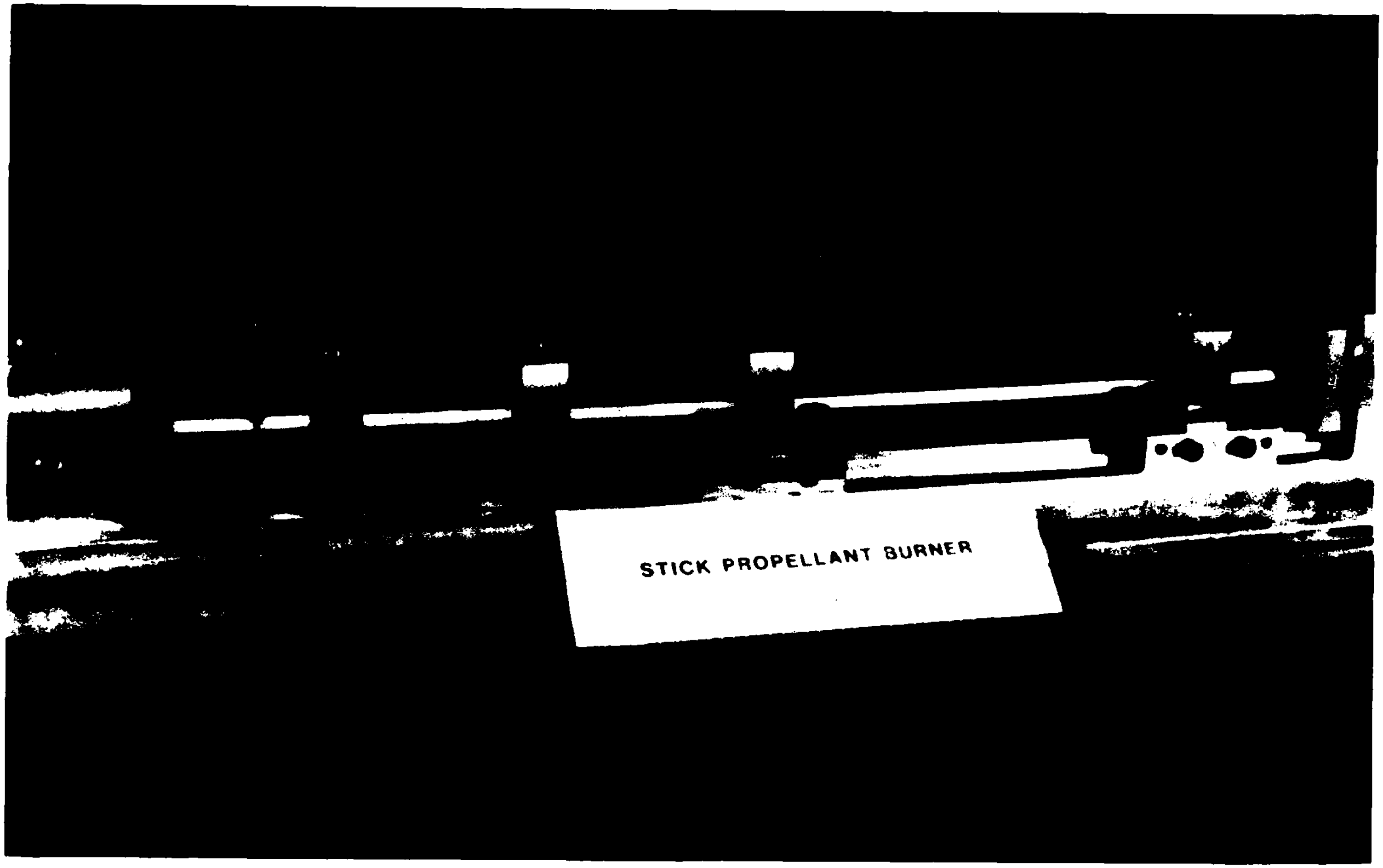

Figure 2. Experimental Device for Measuring Pressure Inside the Burning Perforation of an Unslotted Stick Propellant

Figure 3. 155-mm, Short-Barreled Howitzer

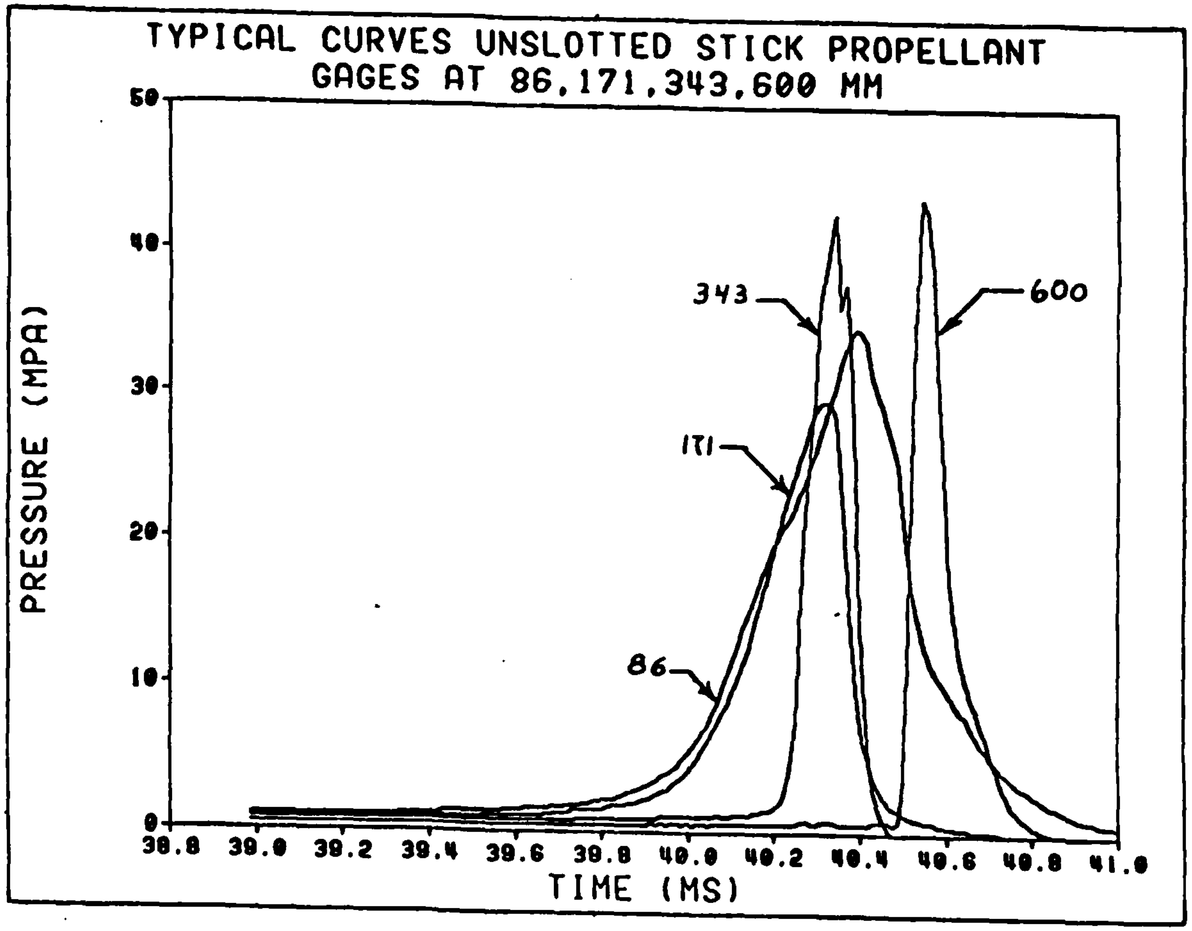

Figure 4. Typical Pressure-Time Curves for Unslotted Stick Propellant Tested in the PIP Device

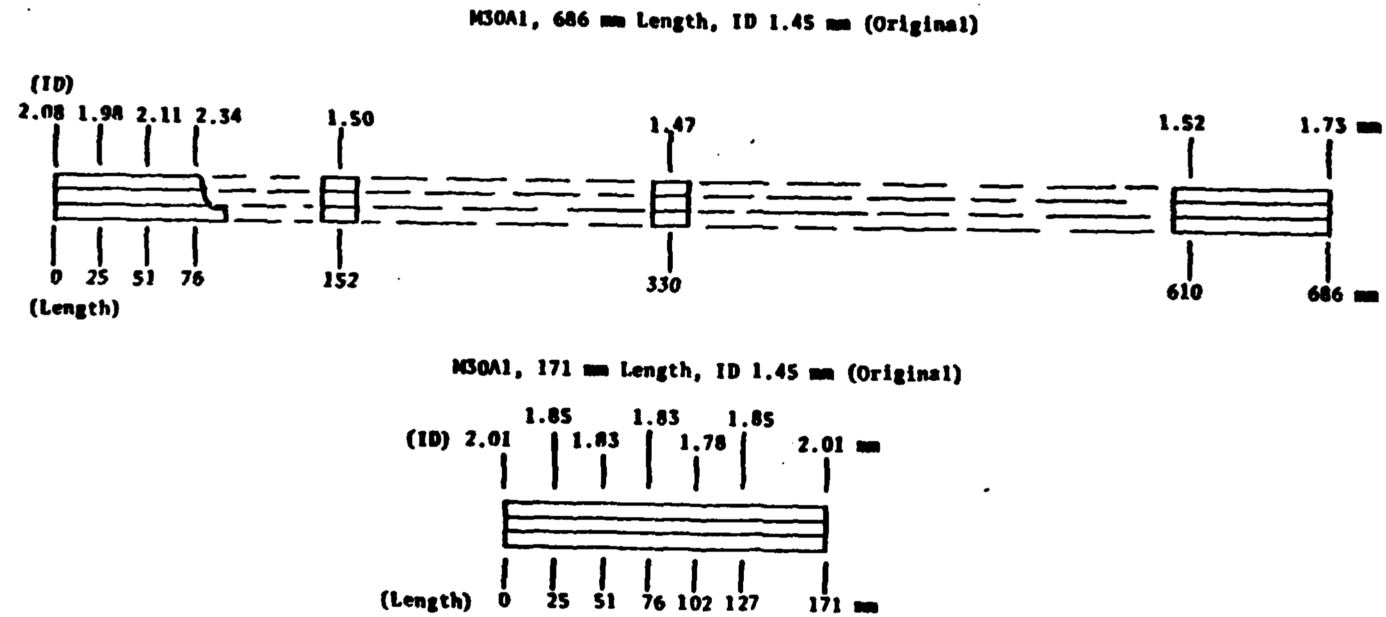

Figure 5. Measurements of Extinguished Pieces of M30A1, Unslotted, Stick Propellant from the PIP Device

TABLE 2. MEASURED PROPELLANT DIMENSIONS

Type	Length (mm)	Perforation Diameter (mm)	Outer Diameter (mm)	Slot Width (mm)
NOSOL 363 Unslotted Small Perforation	686	0.81	6.40	--
NOSOL 363 Unslotted Large Perforation	686	1.96	7.49	--
M30A1 Unslotted RAD 472-12	686	1.50	6.50	--
M30A1 Slotted RAD 472-11	686	1.45	6.53	0.2
M30A1 Slotted RAD 472-10	737	1.45	6.53	0.1

sticks were 44 MPa for the M30A1 propellant and 27 MPa for the NOSOL 363. It would seem reasonable to expect these burst pressures to be applicable to the ballistic environment as well.

Returning now to the test depicted in Figure 4, the pressurization event is seen to travel from left to right, with an apparent velocity over the second half of its travel of 890 m/s. We note that both pressurization rates and maximum pressures achieved increase as the event progresses downstream. It may be postulated, therefore, that ignition and combustion are occurring just behind the pressure front, leading very rapidly to stick rupture and depressurization. Assuming this picture to be correct, then, not surprisingly, some rate dependence of the propellant burst strength can be inferred from the data. However, even at the highest rates of pressurization achieved during this testing, mechanical failure of the propellant sticks accompanies pressures an order of magnitude lower than pressure differentials previously calculated to occur, were fracture not to take place, during the ballistic event.[5]

Measurements of extinguished propellant sticks revealed greater burn distances, perhaps caused by erosion, over the first few centimeters from each end of the stick. Maximum consumption was achieved near the first pressure gage (86 mm), while only a few hundreths of a millimeter was measured at the second gage location (171 mm).

Post-test measurements of a shorter (171-mm), M30A1 propellant stick are also shown in Figure 5. Only one igniter was employed and the stick was blown out of the ignition chamber in one piece during the test. Nevertheless, cone-shaped propellant consumption is noted again at both ends of the stick, further confirming the presence of an erosive (i.e., velocity-coupled) contribution to the burning process in these regions. A single pressure gage at the center of the stick registered 22 MPa before the stick moved, well above earlier static burst pressures[5] but below the dynamic burst levels described above. A second 171-mm stick tested with no

supporting pressure gage at its center and in a configuration which prevented propellant motion resulted in fracture.

Simulations of ignition and pressurization of a full-length (686-mm), M30A1 propellant stick in the PIP device were performed using an experimental version of the NOVA two-phase flow interior ballistic code,[6] developed by Paul Gough Associates, Inc., for the Naval Ordnance Station, Indian Head, MD. Results from calculations are displayed in Figure 6. Times calculated for passage of the pressure front at the various gage locations, as well as the qualitative character of the predicted pressure-time curves themselves, compare quite favorably with the experimental data of Figure 4. Predicted pressurization rates, however, are somewhat lower than actually measured. On this point, Gough[6] has suggested that his choice of jump conditions at the exit plane of the perforation was motivated by simplicity and may need to be modified as more experimental data become available. Another contributor to the disparity may simply be the use of incorrect low-pressure burning rates.

B. Measurements of Propellant Strain

An attempt was made to develop a technique for direct use of strain gages bonded to the outer surface of the propellant stick to yield data from which one might infer the pressurization profile within the perforation prior to fracture. A principal advantage of this technique is the removal of the supporting hardware used to clamp the pressure gages to the propellant sticks. Initial results were encouraging, in that strain profiles mimicked the corresponding profiles, both in time and shape, recorded by adjacent pressure gages. Problems yet to be overcome, however, include calibration of the strain gage, nonlinearity of the bridge circuit for large changes in resistance, and difficulty in determining propellant rupture times. At the very minimum, the strain gages serve as convenient event markers for the onset of pressurization and indicators of tension or compression at the time of propellant failure. Strain data for a full-length, M30A1 propellant stick, ignited this time at the right end, are presented in Figure 7.

C. Short-Barreled Howitzer Tests

Firings were conducted in the 155-mm, short-barreled howitzer described previously using several lengths of both M30A1 and NOSOL 363 stick propellant. A first series made use of the same total charge weight, 9.52 kg, of either full-length (686-mm) sticks or a combination of 86- and 171-mm long sticks stacked in bundles as shown in Figure 8. A second series employed various charge weights of the same M30A1 stick propellant lot. High-speed cinematography (5000 frames/second) recorded ejection of burning propellant for all tests; the extinguished grains were then collected and

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[6] P.S. Gough, *"Extensions to NOVA Flamespreading Modeling Capacity," Task I Report for the Naval Ordnance Station, Indian Head, MD, Contract N00174-80-C-0316, Paul Gough Associates, Inc., Portsmouth, NH, April 1981.*

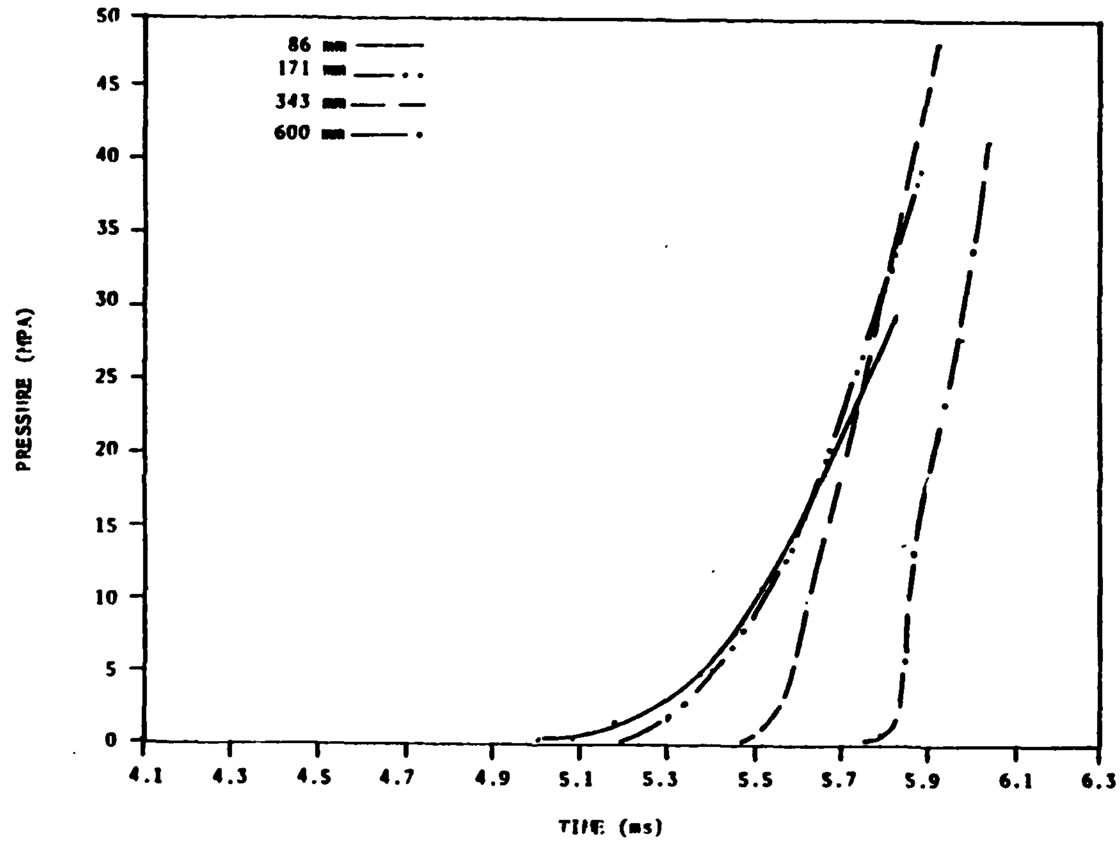

Figure 6. NOVA Simulation of Pressure-Time Curves Inside the Perforation of an Unslotted, M30A1 Stick Propellant

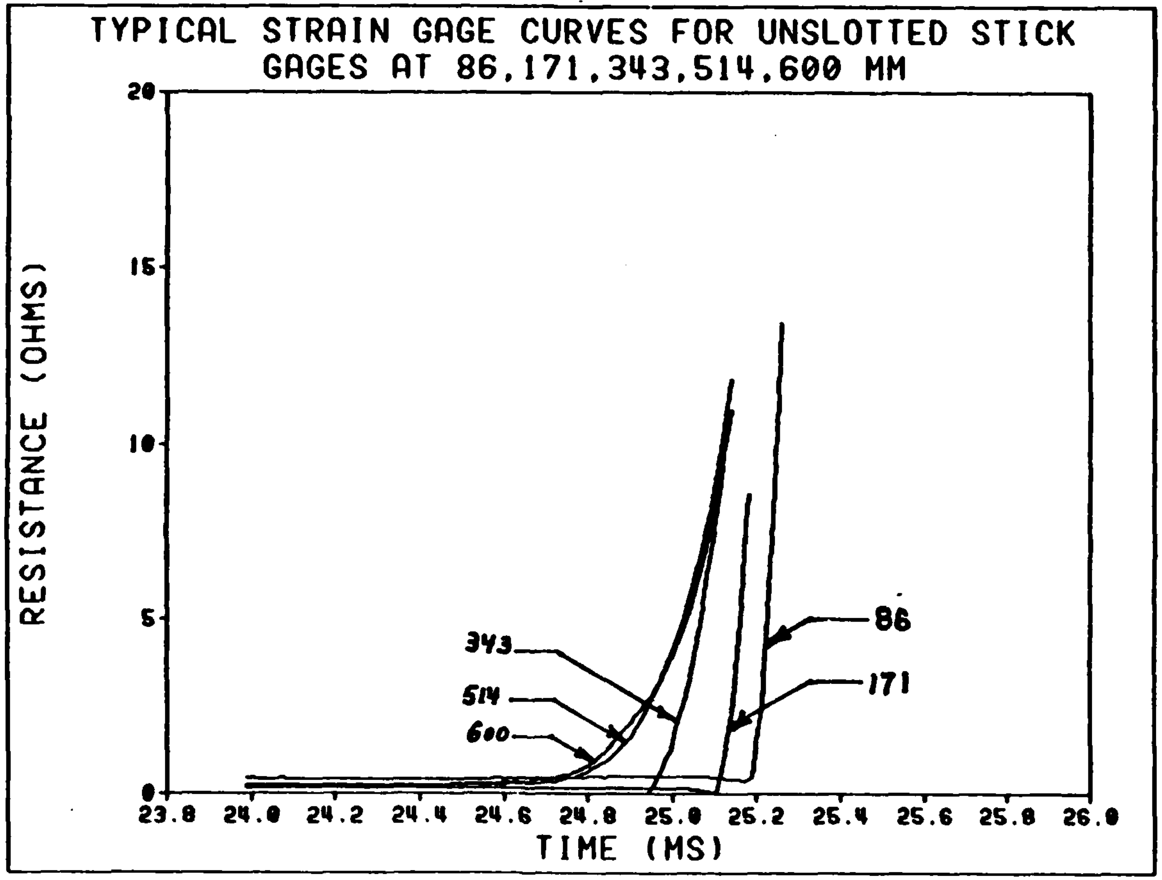

Figure 7. Strain Gage Output for a PIP Firing of an Unslotted, M30A1 Stick Propellant

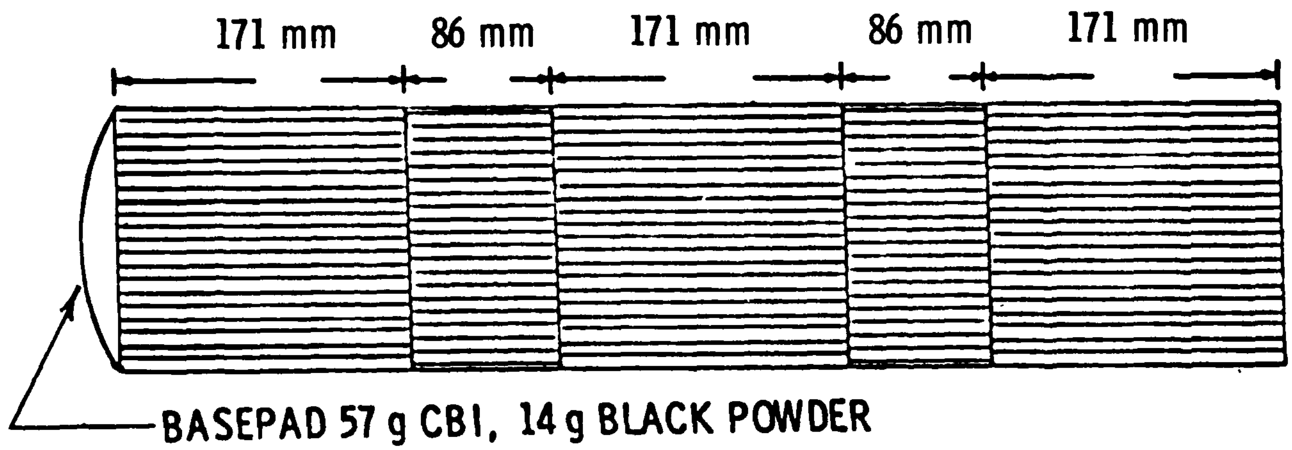

Figure 8. Test Configuration for 86- and 171-mm Propellant Sticks in the Short-Barreled Howitzer

measured. Photographs of the extinguished grains are included as Figures 9 through 20. Maximum pressure and measured dimensions for the two series are provided in Tables 3 and 4. In addition, a typical set of pressure-time profiles is presented in Figure 21. We note that pressures at the breech and mid-chamber positions were nearly the same for all stick firings. (An M203 granular propellant charge, fired as a reference round, exhibited the expected, larger gradient between these positions.)

Returning to the photographs of extinguished propellant sticks, remnants of full-length and short sticks from M30A1 Lot RAD-472-12 fired during the first series are seen in Figures 9 and 10, respectively. Close examination of the propellant fragments allowed determination of whether or not a surface generated by fracture had undergone any subsequent burning. Extinguished pieces from the full-length firing, with a maximum length of about 150 mm, all showed evidence of combustion after fracture. The self-generated slots had burned about the same distance as had the outer surfaces of the sticks, indicating that splitting had occurred very early in the burning process. While no unbroken full-length sticks were collected, about 90 per cent of the short sticks recovered remained intact. Some of the short sticks did exhibit splitting and holes, and all experienced a coning effect of as much as 0.5 mm for the first 25 to 50 mm at each end. Interestingly, the 86-mm sticks from the short stick tests must have burned completely, as none were recovered. We call attention to the difference in maximum pressures (Table 3) for the two charges, providing additional evidence of propellant splitting during the burning process for the full-length sticks.

Figures 11 and 12 display the recovered stick fragments from similar firings employing the large-perforation NOSOL 363. Again, no unbroken, long sticks were found, and the pieces exhibited both splitting and evidence of burning early in the ballistic cycle. Measurements taken on the pieces indicated somewhat greater burn distances within the perforation than on exterior surfaces. Short sticks of both lengths were found, though very few were of the shorter 86-mm length. Coning could be observed only on the 171-mm sticks. A dependence of maximum pressure on stick length was again noted, though not as great as for the M30A1 propellant. This result is consistent with the reduced level of fracture observed for the NOSOL 363 propellant in the PIP tests.

Photographs of propellant remnants from the small-perforation, NOSOL 363 firings are shown in Figures 13 and 14. As before, only a few of the 86-mm sticks were recovered, which this time did show some evidence of coning at the ends of the perforations. Otherwise, burn distances for the 86-mm sticks were the same on both interior and exterior surfaces. However, with the full-length and 171-mm, small-perforation sticks, significantly greater burn distances inside the perforation than on exterior surfaces were measured, again consistent with the calculations. In a related study[7] a

[7] *A.A. Juhasz, F.W. Robbins, R. Bowman, J. Doali, and W.P. Aungst, "Combustion Characteristics of NOSOL 363 Single Perforated and Slotted Stick Propellants," 19th JANNAF Combustion Meeting, CPIA Publication 366, Vol I, pp. 427-442, October 1982.*

TABLE 3. DATA FROM SHORT-BARRELED HOWITZER TESTS - SERIES I

Propellant	Charge Mass (kg)	Breech Pressure (MPa)	Mid-Chamber Pressure (MPa)	Forward Pressure (MPa)	Change in Dimension ID (mm)	OD (mm)	Slot (mm)
M203 Charge M30A1 Granular RAD 77G-69805	11.86	293	281	234	not measured		
M30A1 Stick RAD 472-12 686-mm Long	9.52	269	268	224	1.88	1.85	--
M30A1 Stick RAD 472-12 86-, 171-mm Long	9.52	191	187	165	1.73*	1.63	--
NOSOL 363 Large Perf 686-mm Long	9.52	186	187	161	1.88	1.68	--
NOSOL 363 Large Perf 86-, 171-mm Long	9.52	165	162	131	1.42*	1.55	--
NOSOL 363 Small Perf 686-mm Long	9.52	197	197	152	1.96	1.57	--
NOSOL 363 Small Perf 86-, 171-mm Long	9.52	184	180	158	2.01*	1.63	--
M30A1 Stick RAD 472-11 686-mm Long	9.52	203	200	lost	1.63	1.75	1.78
M30A1 Stick RAD 472-11 86-, 171-mm Long	9.52	201	198	175	1.70	1.70	1.85

*These sticks exhibited significant coning at the ends; measurements reported were taken at the center of the grain.

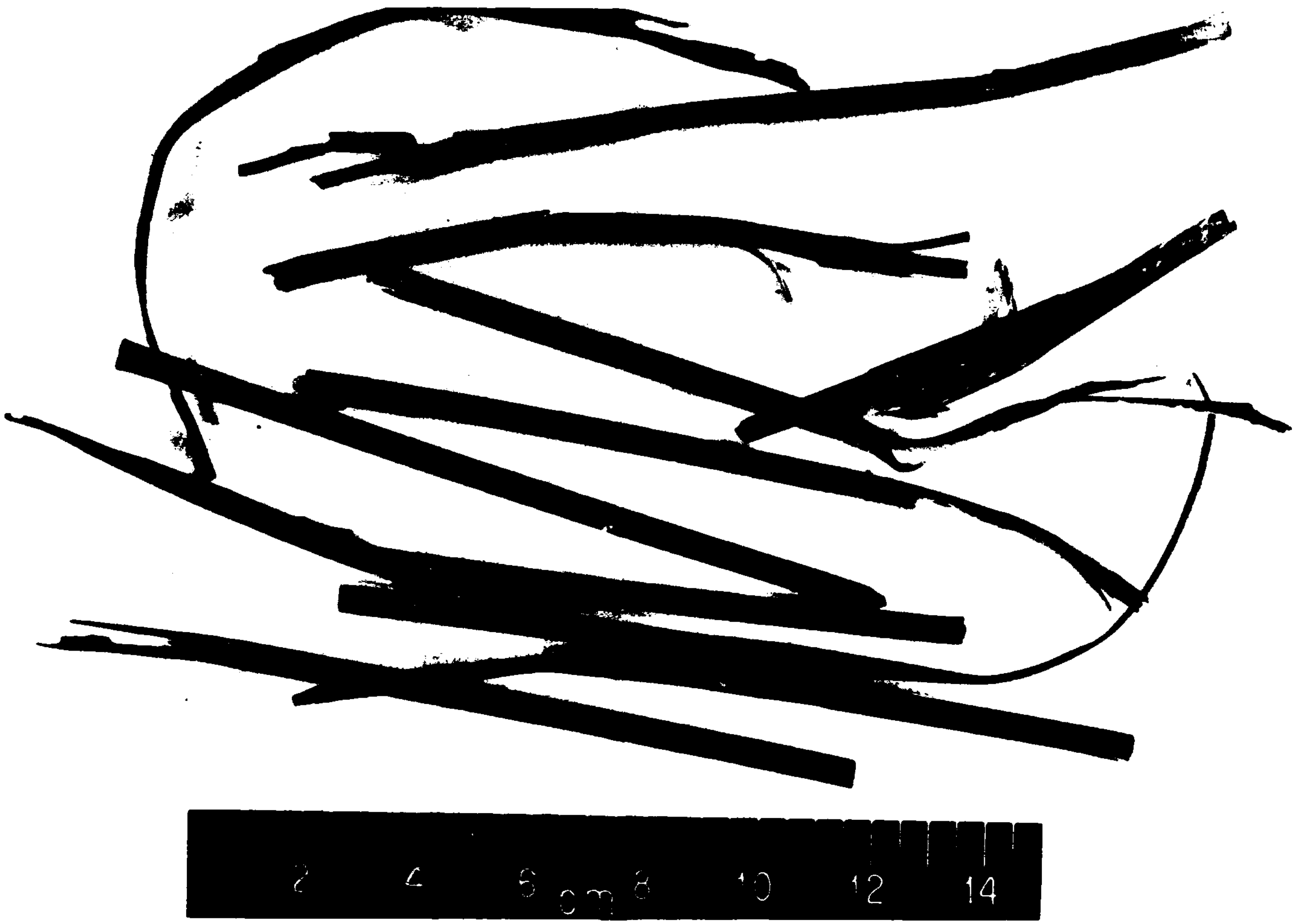

Figure 9. Extinguished Pieces of Long, Unslotted, M30A1 Stick Propellant, Lot RAD 472-12

Figure 10. Extinguished Pieces of Short, Unslotted, M30A1 Stick Propellant, Lot RAD 472-12

Figure 11. Extinguished Pieces of Long, Large-Perforation, Unslotted, NOSOL 363 Stick Propellant

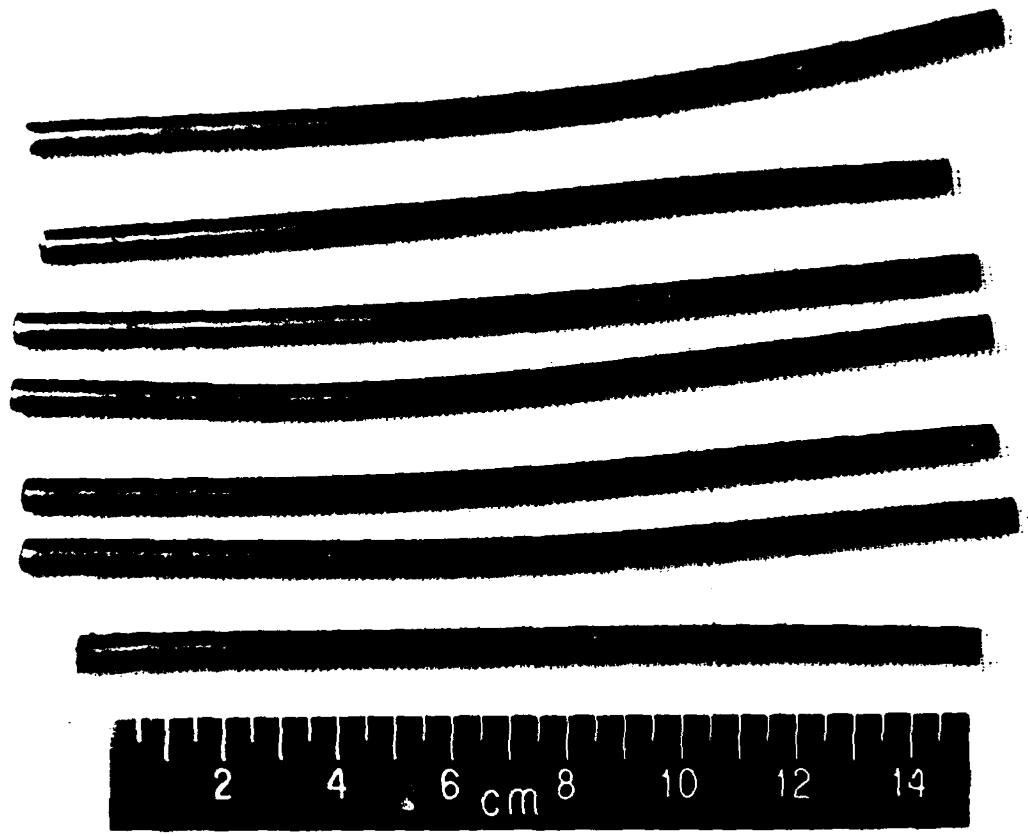

Figure 12. Extinguished Pieces of Short, Large-Perforation, Unslotted, NOSOL 363 Stick Propellant

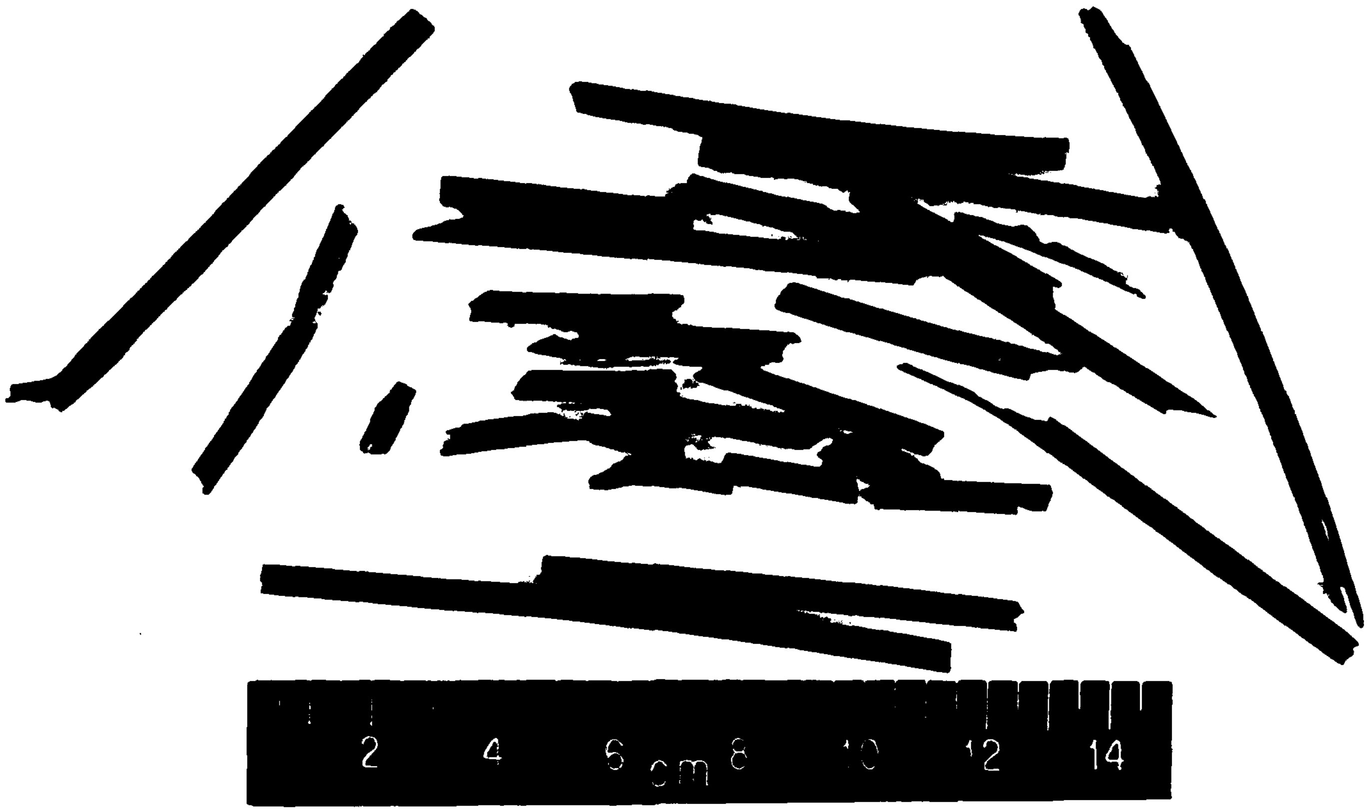

Figure 13. Extinguished Pieces of Long, Small-Perforation, Unslotted, NOSOL 363 Stick Propellant

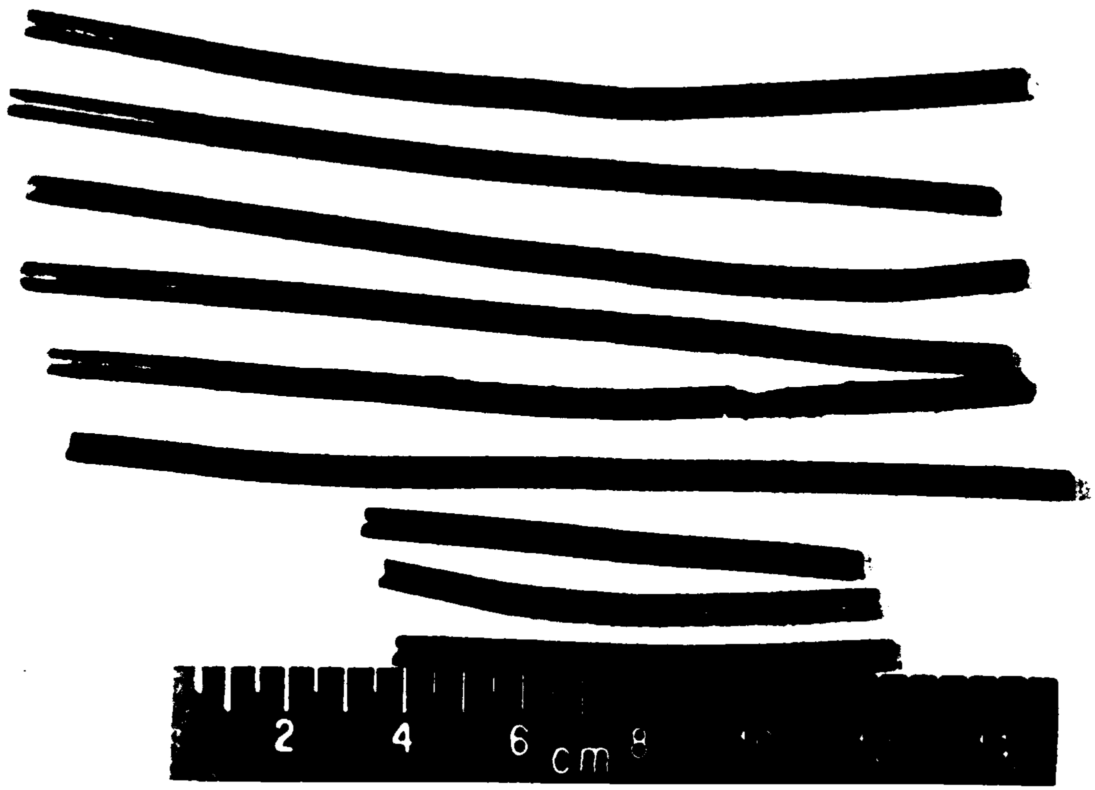

Figure 14. Extinguished Pieces of Short, Small-Perforation, Unslotted, NOSOL 363 Stick Propellant

dependence was observed between grain length and extracted, closed bomb burning rates for NOSOL 363 propellant. Enhanced burning within the perforation as well as coning at the ends were again observed in extinguished grains. Some discrepancies between the results of the two studies do, however, remain to be resolved.

Collected fragments from the final two firings of the first series are displayed in Figures 15 and 16. This time slotted, M30A1 stick propellant, Lot RAD 472-11, was employed. While only small pieces of the full-length sticks were recovered, there was no evidence of burning on the fractured surfaces, suggesting that the sticks broke late in the cycle or even after exiting the gun. As with some of the previous firings, no 86-mm sticks were recovered; further, virtually all of the 171-mm sticks were found intact. For all recovered propellant pieces, the measured burn distances within the perforation, on the outer diameter, and on the slot faces were virtually the same - a totally classical picture of surface regression. The recorded maximum chamber pressures corroborate this view, being essentially equivalent to that expected with no burning augmentation or propellant fracture.

A second series of firings (Table 4) with slotted stick propellant was conducted with reduced charge weights in an attempt to recover unbroken, full-length sticks. M30A1 propellant, Lot RAD 472-10, was employed because the supply of Lot RAD 472-11 had been exhausted. As shown in Figures 17 through 20, the quantity and size of recovered pieces increased as the charge weight was reduced, but no unbroken, full-length sticks were ever recovered. High-speed (5000 frames/second) movies of a firing with the

TABLE 4. DATA FROM SHORT-BARRELED HOWITZER TESTS - SERIES II

Propellant	Charge Mass (kg)	Breech Pressure (MPa)	Mid-Chamber Pressure (MPa)	Forward Pressure (MPa)	Change in Dimension ID (mm)	OD (mm)	Slot (mm)
M30A1 Stick RAD 472-10	9.52	197	197	156	not measured		
737-mm Long	8.16	147	141	123	1.37	1.55	1.55
	6.80	lost	lost	lost	1.35	1.45	1.47
	6.80	128	127	110	1.52	1.45	1.65
	5.44	112	108	91	1.37	1.40	1.52

lowest charge weight (5.44 kg) revealed that the sticks did exit the gun intact but apparently broke as they tried to bend and follow the radially expanding muzzle flow. (See Figure 22.) For larger charge weights, the exiting propellant was obscured by flash, but it is assumed that a similar, even more vigorous event occurred, leading to the greater amount of fracture and scattering. Measurements of recovered propellant fragments again revealed a nearly uniform regression on all surfaces, though a surprising result was that it was also the same for all charge weights fired.

Figure 15. Extinguished Pieces of Long, Slotted, M30A1 Stick Propellant, Lot RAD 472-11

Figure 16. Extinguished Pieces of Short, Slotted, M30A1 Stick Propellant, Lot RAD 472-11

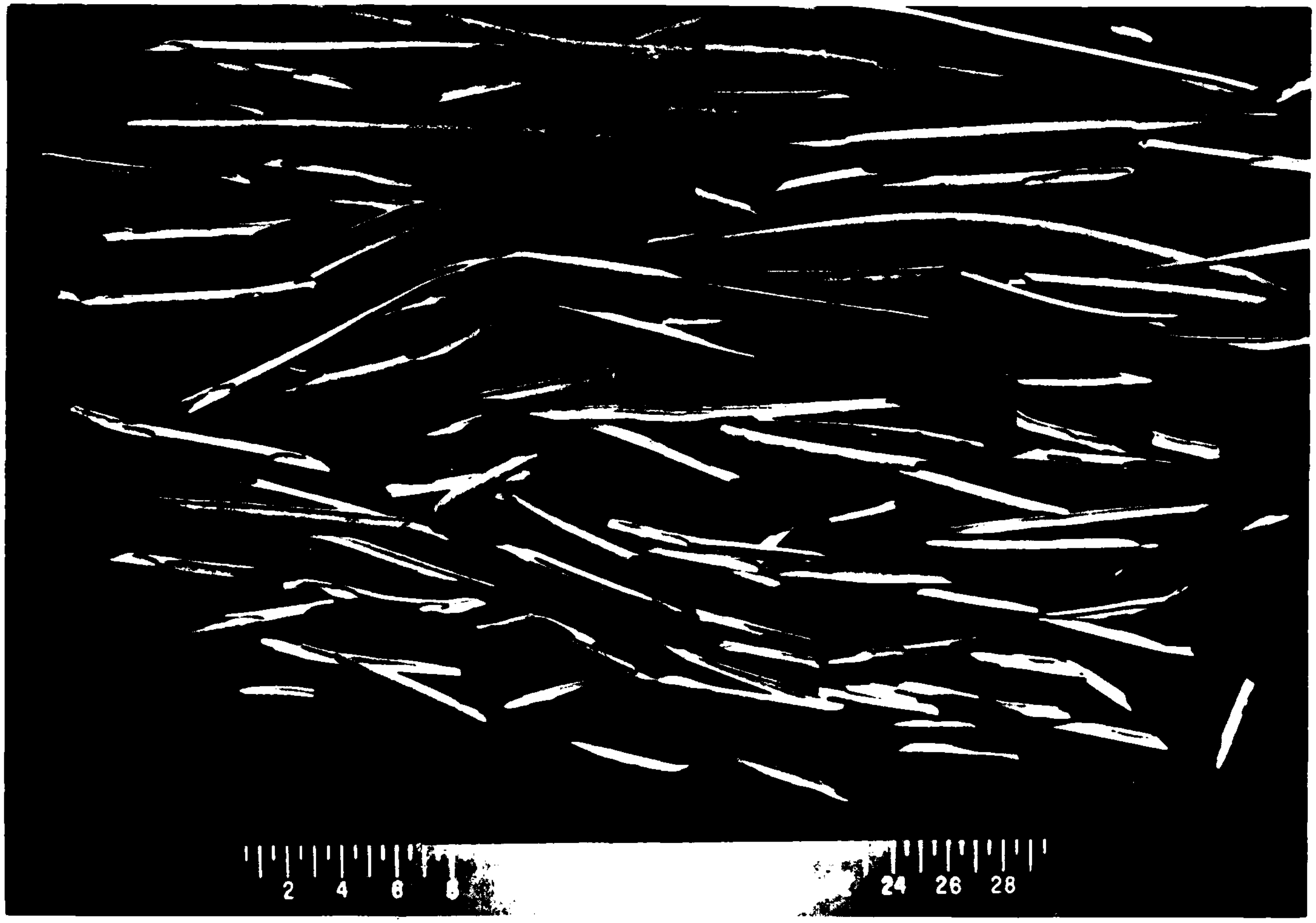

Figure 17. Extinguished Pieces of Slotted, M30A1 Stick Propellant, Lot RAD 472-10; 9.52-Kg Charge

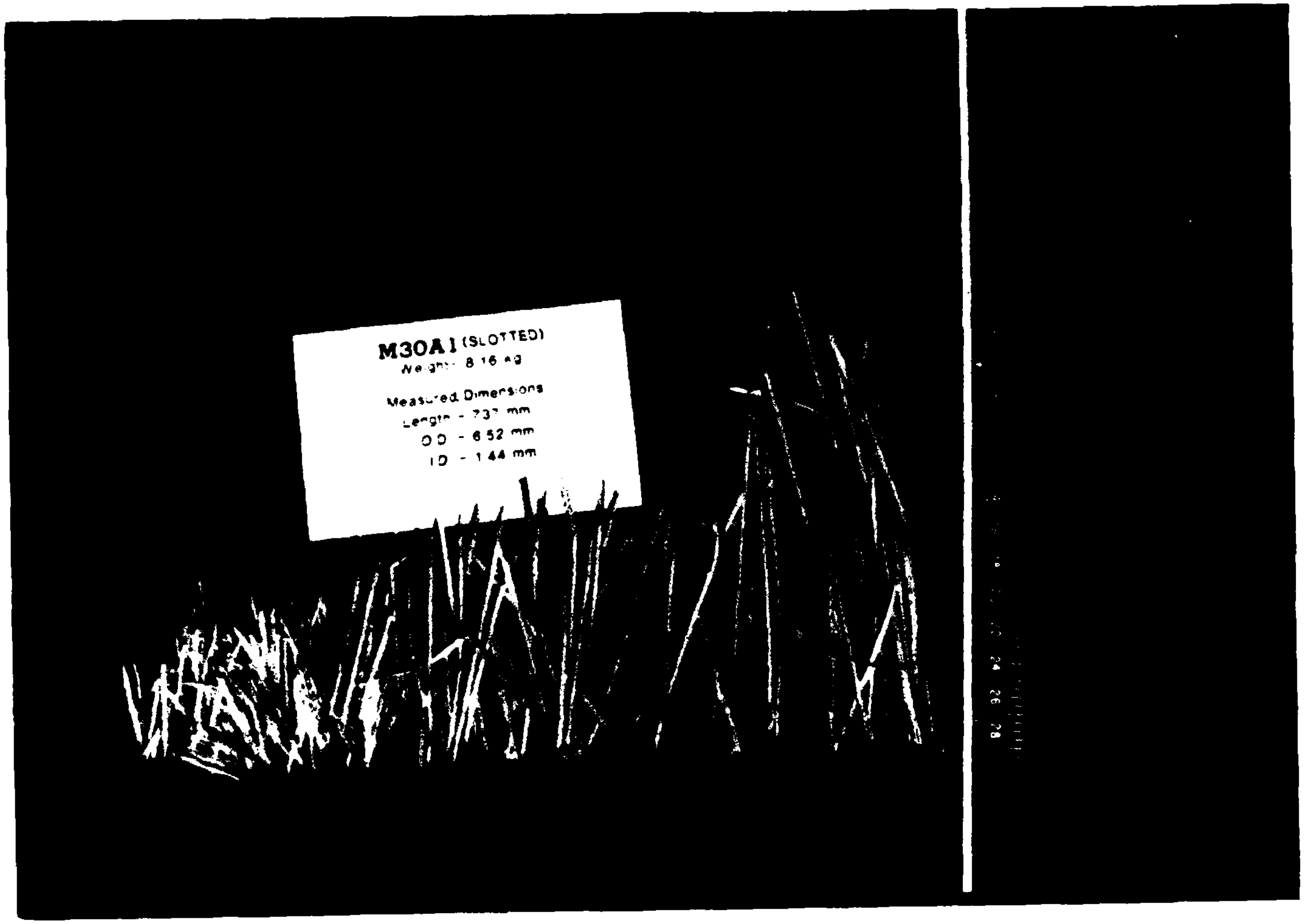

Figure 18. Extinguished Pieces of Slotted, M30A1 Stick Propellant, Lot RAD 472-10; 8.16-Kg Charge

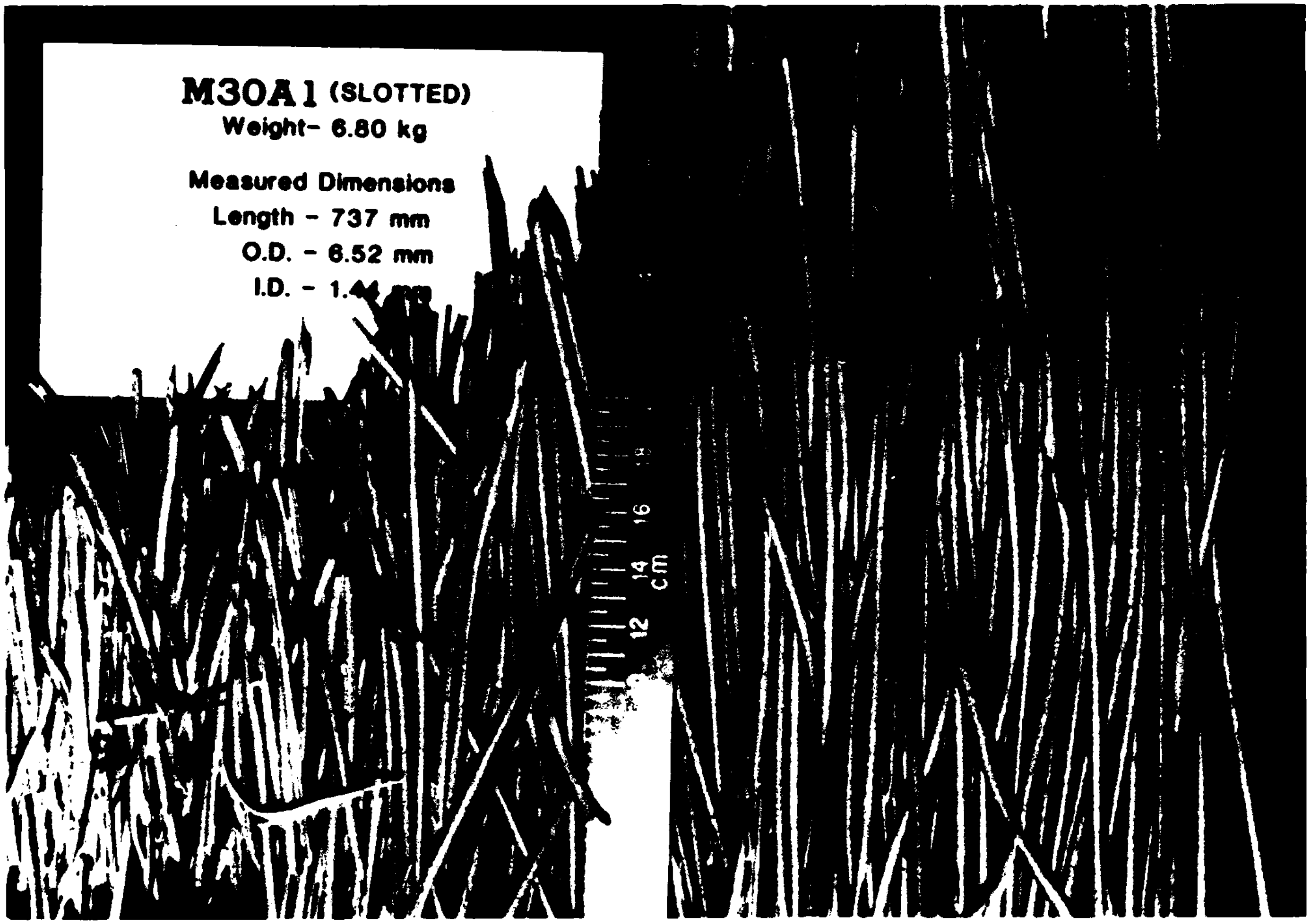

Figure 19. Extinguished Pieces of Slotted, M30A1 Stick Propellant, Lot RAD 472-10; 6.80-Kg Charge

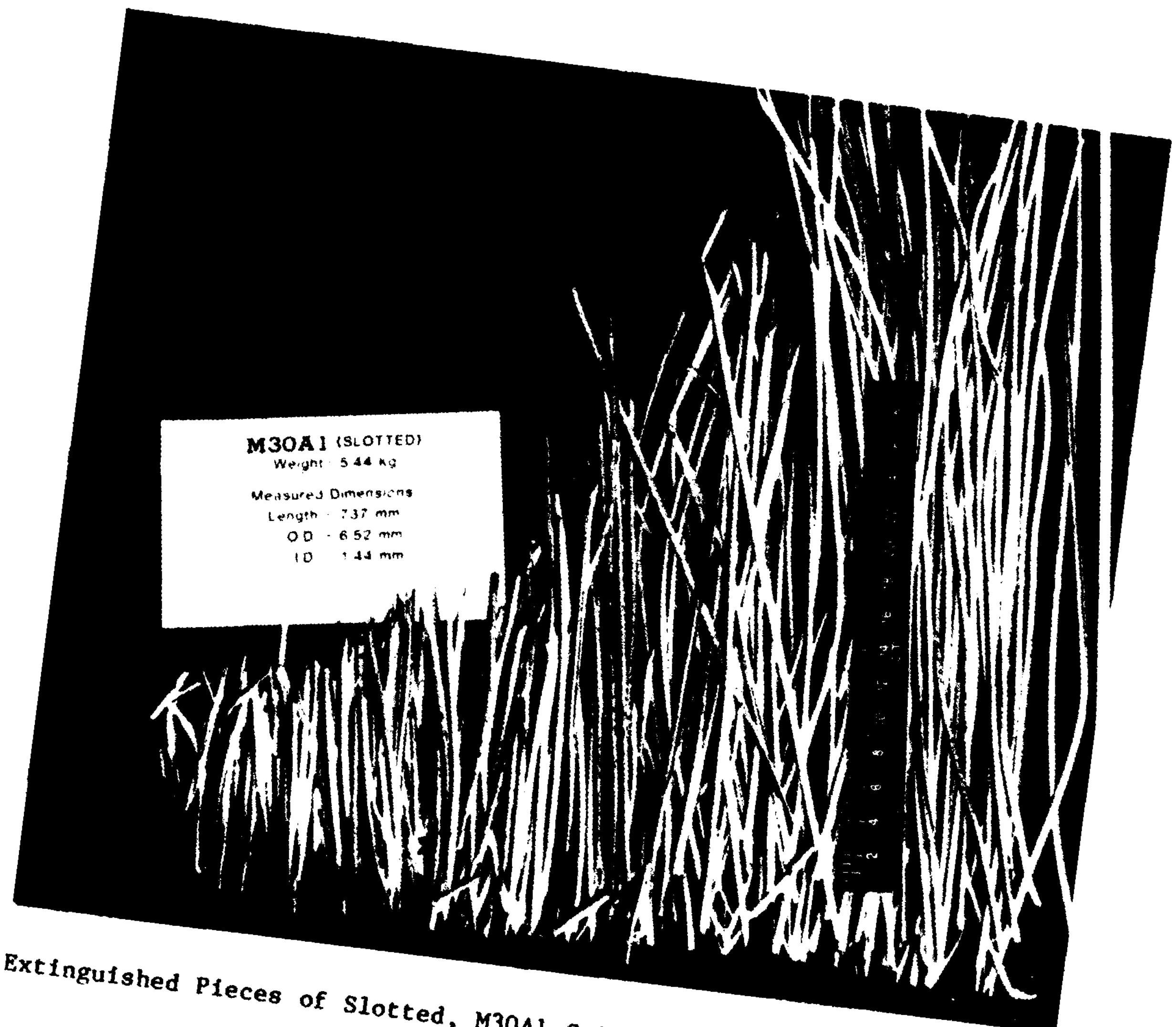

Figure 20. Extinguished Pieces of Slotted, M30A1 Stick Propellant, Lot RAD 472-10; 5.44-Kg Charge

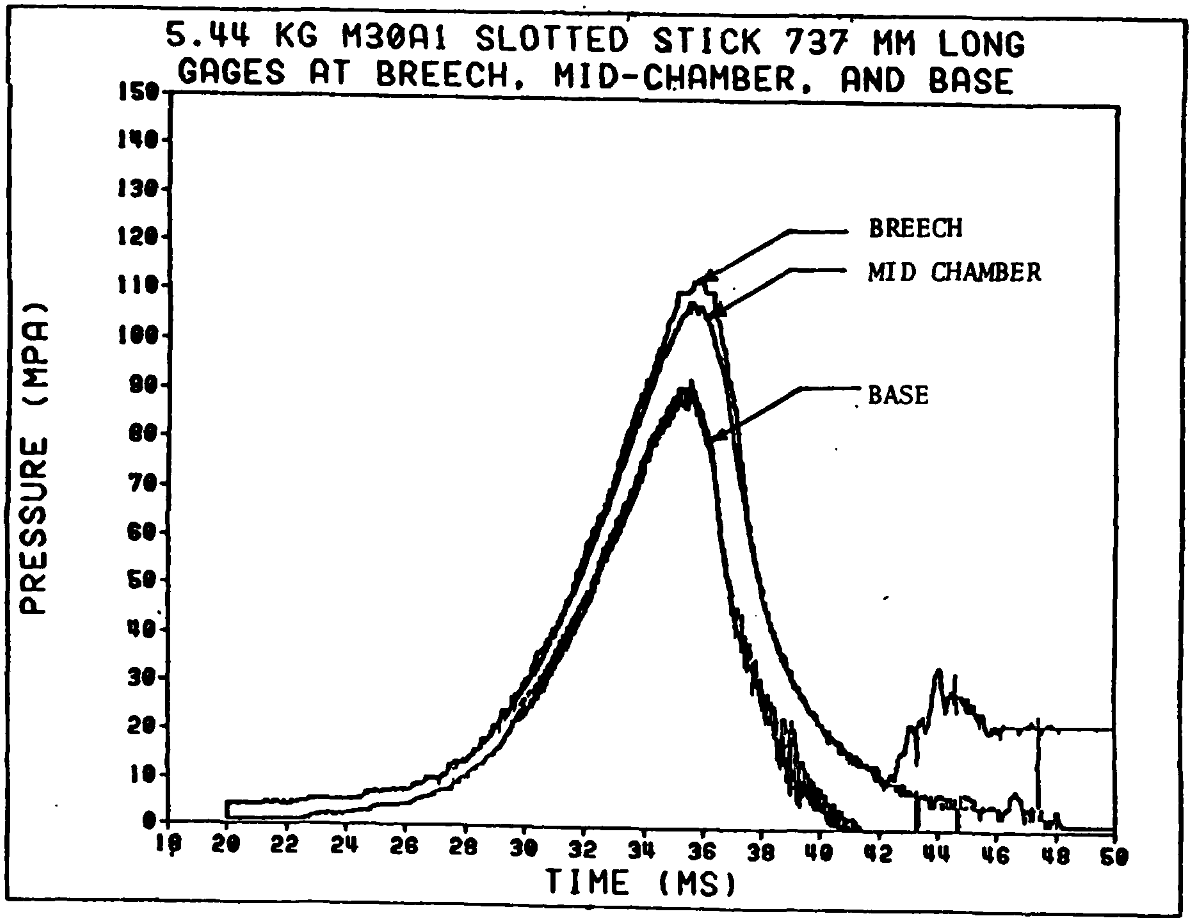

Figure 21. Typical Pressure-Time Curves from Stick Propellant Firing in the Short-Barreled Howitzer

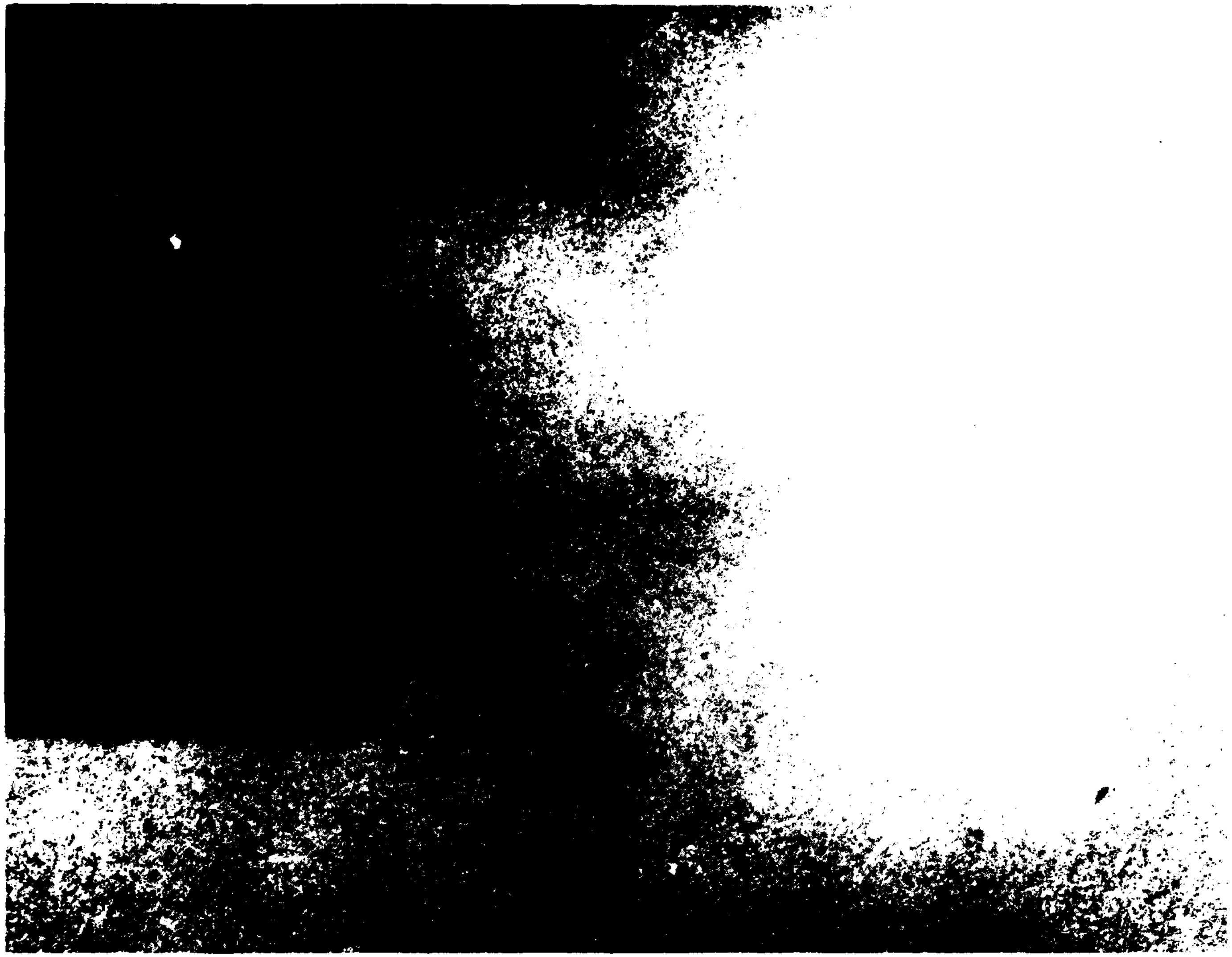

Figure 22. Slotted, M30A1 Stick Propellant Exiting the Short-Barreled Howitzer

IV. CONCLUSIONS

Long, unslotted stick propellant with nominal perforation diameters splits early in the interior ballistic cycle generating increased surface area. This mechanism accounts for the major increase in observed maximum chamber pressure over that calculated using classical interior ballistic theory. Coning at the ends of and augmented burning within the perforation both occur in those sticks which do not split, but are second-order effects.

Short, unslotted stick propellant does not split during the interior ballistic cycle. When about 170-mm long, these sticks exhibit both coning and augmented burning within the perforation. Gun firings conducted with this propellant yield very nearly the expected maximum chamber pressure, but, as previously noted with unslotted stick propellant,[8] result in a muzzle velocity some 3 or 4 percent higher than calculated with standard lumped-parameter interior ballistic codes.

Long, slotted, M30A1 stick propellant does not split during the early portion of the interior ballistic cycle and probably most often does not split at all until near burnout. Moreover, all burning surfaces regress at the same rate in accordance with classical theory.

The NOVA two-phase-flow interior ballistic code, as modified for stick propellant, provides a phenomenologically more complete treatment of flame-spread and combustion within the perforation of stick propellant. This code and TDNOVA, its two-dimensional derivative, should serve as valuable tools for future study of stick propellant combustion.

V. RECOMMENDATIONS

Further investigation of stick propellant phenomenology is required to determine the source of the increase in muzzle velocity over that predicted by classical theory so that future stick propellant charge designs may routinely realize this potential.

The concept of programmed splitting of stick propellant, triggered by augmented burning within the perforation, appears to warrant exploitation as a technique for achieving a desirable, large increase in burning surface at a late stage in the interior ballistic cycle. Coupled with the extremely high loading densities achievable with such geometries as hexagonal-shaped, perforated stick propellant, this very-high-progressivity concept may offer, in addition to the previously mentioned advantages of stick propellant, valuable increases in performance as well.

---

[8] *S. Einstein, Personal Communication, USA ARRADCOM, Dover, NJ, August 1982.*

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